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A tribute to Professor Alex H Johnstone (1930–2017)

His unique contribution to chemistry education research

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Abstract:
In a symposium at the Warsaw ECRICE meeting in Warsaw in September 2018, the enormous contribution made by the late Professor Alex H Johnstone was celebrated and the impact he made exemplified by contributions from recent research. This paper summarises his unique contribution to chemistry education research.

Keywords: chemistry education research, information processing, understanding chemistry, working memory

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His early career

After graduating with first-class honours in chemistry and following mandatory army experience, Johnstone entered secondary school chemistry teaching in Scotland in the late 1950s, spending many years in this area. The secondary school teaching profession in Scotland was, and is, an all-graduate profession and Johnstone spent many years as a "*Principal Teacher of Chemistry*" where he led a team of four other graduate chemists as they started to teach a recently developed curriculum (SEB, 1962a). Many countries developed new curricula in the sciences about that time but Johnstone himself had had a major input into the development in Scotland, an unusual feature in that most school curricula in most countries, even today, have little input from practising teachers.

The curriculum was a remarkable success: the numbers choosing to study chemistry (as well as physics: (SEB, 1962b) rose rapidly, a popularity pattern that still is present in Scottish education today. Johnstone was invited all over the country to present workshops for practising teachers of chemistry as this new curriculum was introduced during the 1960s. Arising from this, working with a close colleague, he wrote a set of five textbooks to support the course (Johnstone & Morrison, 1965–1969). This set of textbooks took a very different approach compared to traditional texts. It allowed learners to engage with the ideas of chemistry, to see how chemistry related to life around and to understand the way the experimental underpins our understanding of our world.

One of his great insights was to develop a curriculum that was based on *guided discovery learning*. Discovery learning allows students to explore their world freely. By contrast, guided discovery learning allows the teacher a key role in directing the students as they explore their world. The aim was to allow the young learners to look at the world around from the perspective of chemistry and to see what insights and understandings chemistry offered in making sense of *their* world. Much was built around experimental work. Here, the goal did not focus on the the conduct of set experiments to teach practical skills, together with formal reports. Experimental work was totally integrated into class teaching and the experimental was employed to pose questions, to offer answer to questions and to generate understandings. Later research revealed just how successful this had been (Johnstone & Wood, 1977).

New Scottish Chemistry Curriculum (1962)
based on:
- Guided discovery learning
- The central role of experimentation
- Developing intellectual skills beyond recall

As part of the new chemistry curriculum, another new course was set up in the late 1960s, building on the earlier courses.[1] This 1 year course was designed overtly to minimise content to be covered and laid greater

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emphasis on thinking skills and the preparation for independent study in higher education (CSYS, 1969). As part of this, a project was built in (25 % of the credit) and Johnstone developed exciting and practical ways to assess this. This curriculum was indeed radical and proved to be an outstanding success. Sadly, later revisions by those who lacked his incisive vision and understanding of young people lost some of the good features.

Early university teaching

In 1969, Johnstone was invited to move to the Chemistry Department in the University of Glasgow and start a programme of research relating to the new curriculum. It had been noticed that the chemistry courses in the new 1962 curriculum had some interesting effects:

- Teachers found the courses exciting to teach
- Students found the courses exciting to learn
- The popularity of chemistry was growing

  but
- Students found some areas very demanding

His first task was to identify the areas where the curriculum was found to be demanding (Johnstone, 1971) and then he started to develop programmes to search for ways to assist learners in these areas. His approach was simple, yet powerful, and has been applied in several other subject disciplines (e.g. in biology: Johnstone & Mahmoud, 1980).

In chemistry, some key areas were found (Johnstone, Morrison, & Sharp, 1971):

Topics related to equations and the mole
Areas in thermodynamics
Redox, E°s and ion electron ideas
Some organic topics
(esters, proteins, amines and carbonyls, aromaticity)

The areas of difficulty were now established. The next questions was to ask “*why*?” Research students came to work with him in Glasgow and he allocated the areas of difficulty to these students, with the task of trying to find out the nature of the problems and to find any ways to make life better for the learners. In this, he followed no pre-determined ideas. His mind was open. His students (most undertaking PhDs) gathered vast quantities of quantitative evidence and, bit by bit, the picture became clearer. Building on the work of many, the breakthrough came with a very able student who suddenly started to see patterns in the data she had gathered. The common feature in all the areas of difficulty was that they were of “*high information load*” but this concept needed clarification. She was nearing the end of her PhD and her work was published as an hypothesis (Johnstone & Kellett, 1980). It fell to the next PhD student to test this hypothesis out.

The central logic is this (Figure 1):

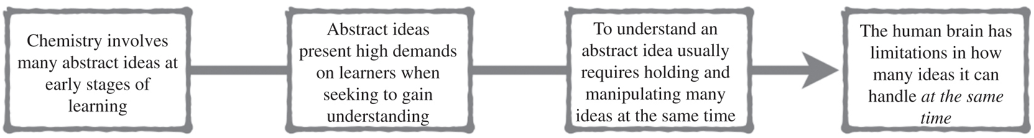

Figure 1: The early breakthrough.

In one part of the following PhD, the student success rate (% of the students who obtained the right answer) was plotted against the information load for all the questions asked. The information load can be seen as: the sum of pieces of information in question, the additional pieces to be recalled and the processing steps (Johnstone & Elbanna, 1986, 1989).

Figure 2 shows the kind of graph they obtained. There is a very marked drop in performance when the information load of the question exceeded about 6.

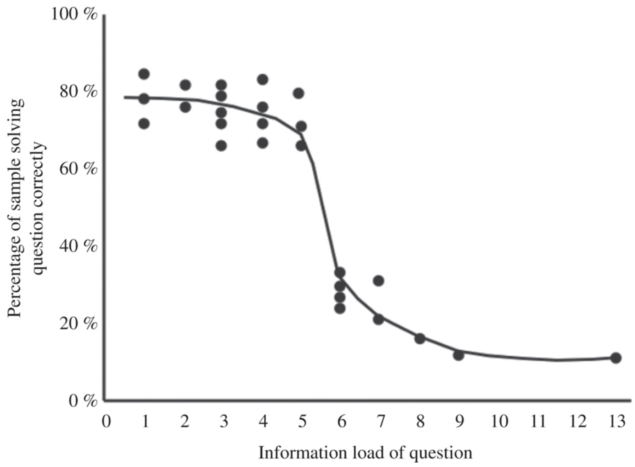

Figure 2: Performance and information load.

Johnstone had *expected* the success rate to fall as the question information load (they called this "*complexity*") increased. What was unexpected was the *sudden* collapse in performance when the information load reached about 6. This illustrates beautifully what happens when the working memory is overloaded. We cope fine and then, when the number of pieces of information gets to be near the capacity of working memory, performance suddenly collapses.

However, the study went further. The working memory capacity of the students (N = 271) had been measured. They employed the approaches successfully developed by Miller (1956) and, like him, found that most of the students could hold 6, 7 or 8 "*chunks*" of information in their minds *at the same time*. They divided their student group into three groups:

- Those with above average working memory capacity (>7);
- Those with average working memory capacity (7);
- Those with below average working memory capacity (<7).

Their graph is shown in simplified form (Figure 3):

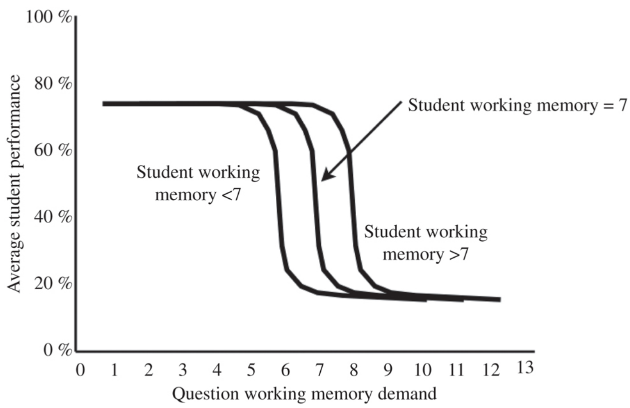

Figure 3: Performance information load and working memory capacity.

This shows clearly that it is the working memory capacity which is *controlling* success. Those with *below* average working memory capacities tended to fail with questions where 5 or more chunks of information were needed while those with *above* average working memory capacities did not fail until the demand of the questions exceeded 6 chunks (Johnstone & Elbanna, 1986, 1989). This was the breakthrough which was needed and this relates to much useful work (for example: Chen & Whitehead, 2009; Danili & Reid, 2004; Overton & Potter, 2008; Scardamalia, 1977; Stamovlasis & Tsaparlis, 2000).

Thus, one clear reason for difficulties in learning (when seen as understanding) is the limitation brought about by working memory capacity. Inadvertently, the new Scottish curricula, in laying a much higher emphasis on understanding, had not only generated increased student interest but also created some areas of difficulty. It was becoming clear that difficulties in conceptual understanding arise from information overload.

What the work directed by Johnstone had now demonstrated was a central principle in all learning:

Fundamental Principle

Extent of understanding is controlled by the limited capacity of working memory

Johnstone then started to search the literature to gain insights from research about how the human brain worked when learning. The paper by Miller (1956), perhaps one of the most cited papers in all academic literature, holds the key. Here, Miller refers to "*short-term memory*" but this was later re-named as "*working memory*". This part of the brain is where we hold and process information before storing it (or maybe not storing it) in long-term memory. Building on the earlier research of Atkinson and Shiffrin (1968), Johnstone developed his now famous information processing model (Figure 4).

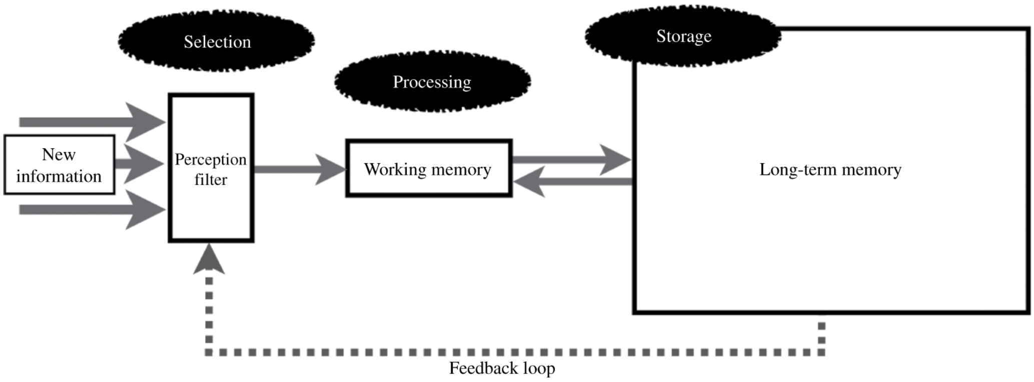

Figure 4: Information processing in the human brain (Johnstone, 1997).

Evidence from studies in numerous areas shows that humans take in information and this passes through what Johnstone described as a "*perception filter*". This selects what will be passed on to the working memory, the selection being determined by what the person already knows, understands and considers important. The working memory is where the information is processed before being passed on to the long-term memory for storage. The working memory can draw previously held understandings from the long-term memory to help with the processing. The long-term memory is one vast store of everything we have learned or experienced.

Working Memory
where we
Think
Understand
Solve problems

This information processing model was developed from much research in psychology, medicine and education and is based on extensive evidence (e.g. Ashcraft, 1994; Atkinson & Shiffrin, 1968; Johnstone, 1997). It seeks to show the flow of information in the brain. The implications arising from the model have been discussed (St Clair-Thompson, Botton, & Overton, 2010). Overall, the model has been found to be to be very valuable in prediction and Johnstone applied the model in this way when he started to look at lecturing, laboratory work and group work – three key approaches used in the teaching and learning of chemistry.

Returning to working memory, Miller (1956) had developed robust ways to measure the capacity of the working memory and he showed that the capacity was genetically fixed (growing with age to about age 16), and that it was finite. Most humans can hold between 5 and 9 "*chunks*" of information at the same time, a "*chunk*" being what the individual person perceived as a *unit of information*. It was the brilliance of Johnstone to realise that it was the fixed and finite nature of the working memory that controlled ALL understanding and that this was the key in understanding why certain topics were difficult for students to understand (Johnstone, 1991, 1997):

Difficulties in Understanding Chemistry
will be seen with
Topics where the learners has to hold and process too much *at the same time* in order to gain understanding

Since coming to the Chemistry Department at Glasgow University, Johnstone taught inorganic chemistry while leading research programmes on the learning of chemistry. This is a much sounder way to undertake educational research. Too often, educational research has become detached from the realities of teachers and learners in specific subjects. As a result, little useful emerges.

Arising from his teaching experiences in Glasgow, he worked with a colleague to write a remarkable book on thermodynamics – an area of known difficulty for final year school students as well as university students (Johnstone, MacDonald, & Webb, 1977). Again, this book took a revolutionary approach to the area (Johnstone & Webb, 1977, 2002). With changes in school courses, Johnstone also worked with two colleagues in producing a new school chemistry text (Johnstone, Morrison, & Reid, 1980). This was, perhaps, the first textbook where the presentation of the subject was deliberately designed to reflect the most recent findings from research about how students understand. In this, Johnstone combined rigorous chemistry presented in line with research evidence about conceptual learning and characterised with great empathy for the young learner. Later revisions of the school chemistry curriculum in Scotland led to the book being inappropriate and, sadly, most subsequent books reverted back to the old style of textbooks which presented the subject logically rather than psychologically (Johnstone, 2000b).

The work develops

With the strong support of the Head of the Chemistry Department at Glasgow, Johnstone was encouraged to set up a Centre for Science Education – a research centre whose entire focus was seeking to understand the processes related to learning in highly conceptual subjects like chemistry. Research students were being attracted in considerable numbers from many countries and a coherent programme of research developed where each study built on previous studies to try to develop a clear picture of learning and, more especially, to develop ways by which students of chemistry (and other cognate subjects) could be helped in the exciting but demanding tasks of understanding. Sadly, the Centre was later transferred to the Education Faculty, marginalised and then closed down in 2008.

Johnstone now the applied the information processing model predictively, considering lecturing, laboratory work and group work areas of learning:

Lecturing

In a typical lecture, the lecturer is seeking to transfer considerable amounts of information to a large group of students, the aim being that the students can gain an understanding of the topics covered. An early study showed that, in the average 1 hour lecture, the lecturer spoke about 5500 words of which the average student was able to record about 10 %, the process being inefficient (Johnstone & Su, 1994).

Johnstone realised that information overload was the key reason why understanding was being hindered. This is nothing to do with the total amount of information presented in a lecture. It related to how many ideas students had to hold in working memory *at the same time* in order to gain understanding. He then developed the idea of the *pre-lecture*. Before a lecture series (maybe 6–8 lectures), students went through a pre-lecture where the underpinning ideas from previous studies were revised and key landmarks of the area established. The prediction was that this would help the perception filter to select more efficiently from the new information in the lecture course, thus reducing potential working memory overload. In turn, that would generate better understanding. Studies over 6 years revealed just how powerful this was, the gains in student understanding being very marked when pre-lectures were employed, exactly as predicted by the model (Sirhan, Gray, Johnstone, & Reid, 1999; Sirhan & Reid, 2001).

Labwork

One of his early students had revealed just how little actual learning was taking place in a typical undergraduate laboratory (Johnstone & Wham, 1979). Indeed, the study showed some quite bizarre behaviour as students tried to avoid the discomfort associated with the feeling that they were not coping. This was a matter of concern, given the expense of laboratory work in terms of staffing, time and resources. Johnstone realised that the laboratory work is what he called a "*very noisy*" place: students are simply bombarded with information: from a manual, the laboratory environment and equipment, as well as demonstrators, along with the need to try to make sense of the chemistry involved. Working memories were simply being overloaded, leaving no capacity for any thinking or understanding. The student was reduced to following the laboratory manual like a recipe book in order the gain "*right*" answers. The information processing model predicted, again, that working memory overload would be reduced if the perception filter was able to operate more efficiently. This led to the pre-lab.

A pre-lab is a short exercise completed *before* the lab where the underpinning ideas were revised, the background to the experiment(s) outlined, student completing various tasks to ensure understanding. This meant that, on entering the laboratory, the student had a much clearer idea what they were doing, *and why*, as well as knowing the key observations they needed to make, *and why.* In addition, anxiety was reduced.

Two studies, one in chemistry (Johnstone, Sleet, & Vianna, 1994) and one in physics (Johnstone, Watt, & Zaman, 1998), tested the prediction and the findings were again very marked, with considerable gains in understanding. Indeed, in the chemistry study, projects were introduced into the laboratory, giving the students an opportunity to apply their understanding as well as working in small groups to consider some social application of the chemistry involved. This gave the added advantage of offering experiences in the way teams of scientists work together to solve problems, typical of how the sciences actually work.

Interestingly, the extra time needed to complete the pre-lab exercises generates an even greater *gain in time* in the actual laboratory, giving time for other activities – hence the projects being possible. The pre-lab idea was based soundly on a prediction from the information processing model and is now widely applied across universities in both chemistry and physics and guidance is now available in the development and use of such exercises in chemistry (Carnduff & Reid, 2003).

School laboratories are somewhat different but, even here, the pre-lab idea was extended in a novel way. Training teachers of chemistry in an open university setting poses its own problems and the pre-labs were adapted to create what were called "*paper laboratories*" (Reid & Shah, 2010). These were NOT designed to replace hands-on laboratory work but to act as a *preparation for teachers* (a form of pre-lab) who were about to be required to use laboratory work in schools, practical training being difficult, given that the students were scattered across a very large nation. This model shows good prospects for developing countries.

Group-work

The problem with lecturing as the central mode of teaching is that it does not allow enough scope for the development of important generic skills, much sought after by future employers (Hanson & Overton, 2010; Sarkar, Overton, Thompson, & Rayner, 2016). Numerous group exercises were created and tested with students, at both school and university levels. The work was pioneered by an early PhD student under Johnstone's supervision, but developed in several directions later (Johnstone, Percival, & Reid, 1981).

What research evidence showed from the various studies was that important skills and attitudes did develop. Group-work allows the development of key skills like:

- Critical thinking
- Arguing and debate
- Negotiating
- Compromising

However, the information processing model does not suggest that the group work structure will reduce working memory overload: members work collaboratively but each has their own working memory. Much research from elsewhere confirms that group work shows no overall advantage in knowledge retention or understanding but confirms there are great gains in the development of skills and attitudes (De Bruyckere, Kirschner, & Hulshof, 2015; Johnstone & Reid, 1981).

Summary

Figure 5 summarises the main findings from a large number of studies, many directed by Johnstone.

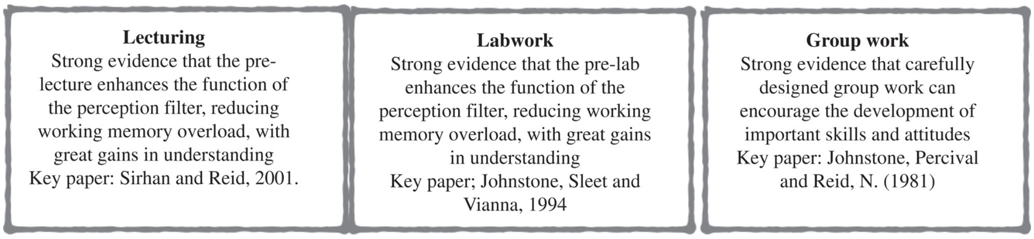

Figure 5: Information processing and traditional learning.

If we look at learning overall, then the work Johnstone directed has shown that the working memory holds a central and critical role in seeking to develop understanding. Given the highly conceptual nature of the discipline of chemistry, this offers the key for teachers as we seek to enable students to move forward successfully (Figure 6):

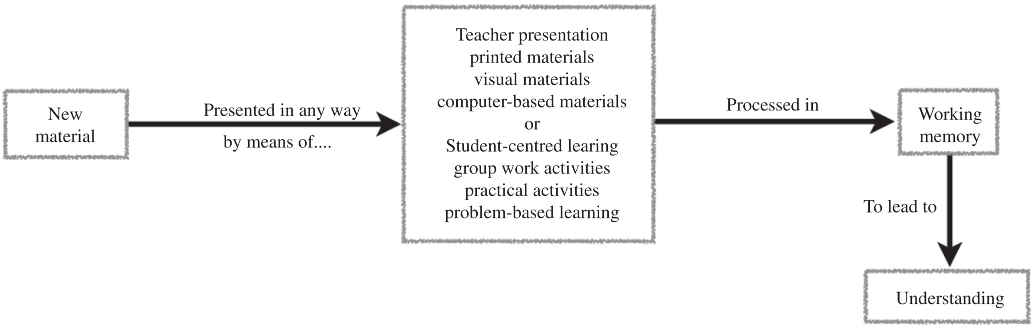

Figure 6: The central role of working memory.

Johnstone's insights

One of his great skills was the ability to look at complex situations and "*see*" the essential key underpinning ideas. We shall look at a few of these. Arising from his long experience in understanding why many students find understanding chemistry so demanding, he developed a very simple model (Figure 7).

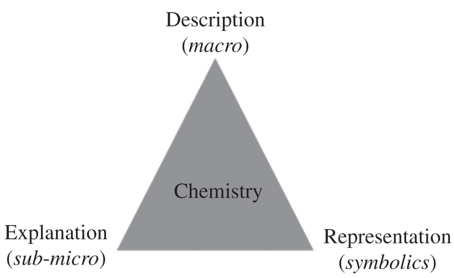

Figure 7: The triangle model.

Chemistry can be seen as having three levels of thought. There is the chemistry we can see, touch and smell. We try to represent and summarise what is happening using various symbolisms (this include equations as well as various mathematical representations). There is also our attempt to make sense of what we observe by developing insights based on entities that we cannot see: atoms, molecules and sub-atomic particles.

This model is often misunderstood. Based on years of research evidence, Johnstone realised that the novice learners CANNOT handle all three levels *at the same time*. This is simply because of the limitations in the capacity of the working memory. He argued that, in the early stages in learning chemistry, we must be very careful not to attempt to bring in explanations and representations until the descriptive aspects are well established.

The young learner at school and university, meeting ideas for the first time, with a limited working memory capacity, simply CANNOT work at all three levels at the same time (Johnstone, 1999). As teachers, we need to focus *on one level at a time*, until the students are secure in their understanding. This is the central message for us all: we need to focus on one level (and then move to 2 levels), during the early stages of learning to allow the working memory to cope (Georgiadou & Tsaparlis, 2000; Tsaparlis, Kolioulis, & Pappa, 2010).

Some examples illustrate this. At early school stages, there is an enormous amount of chemistry that can be discussed, basing things simply on what the young learners see in their experimentation, and then developing patterns and insights from this (Reid, 2000). Once this is well established, the symbolics can be gently introduced and, later, interpretations involving the sub-micro explored.

One area where this was explored was in the learning of organic chemistry. For a student to grasp the descriptive, the representational and the molecular *at the same time* is asking the impossible. What research shows that, if the students have a good grasp of the descriptive (with the use of simple molecular equations), the mechanistic can be built on this foundation at university. Thus, mechanistic approaches should not be introduced until the the fundamental principles are well established. The working memory simply cannot handle all three levels a*t the same time* (Hassan, Hill, & Reid, 2004).

Much of this stemmed from Johnstone's work on pre-lectures and pre-labs. In essence, we need to ensure that fundamental ideas are well established before we start to bring in more ideas. If we fail to do this, then understanding rapidly becomes a casualty and, in order to pass examinations, students resort to memorisation, with concomitant deterioration in enjoyment and fulfilment (Hussein & Reid, 2009; Jung & Reid, 2009). This is almost certainly a major factor that makes the study of chemistry unattractive in some countries.

When a learner has the fundamental ideas well-established, then these ideas are being grouped together to make coherent sense and, thus, occupy less space in working memory (the principle of *chunking*: Miller, 1956). This leaves capacity to build on further ideas. The principle is simple and powerful, as so many of Johnstone's insights have proved to be. The essential fundamental principle is that, in teaching, curricula need to be presented psychologically, rather than just following the logic of the subject (Johnstone & Ambusaidi, 2000).

It is interesting to note that the triangle model here has been adapted for mathematics and biology, both generating tetrahedral models of levels of learning (Ali & Reid, 2012; Chu & Reid, 2012). Where biology has an advantage is that much more can be covered at the descriptive level (especially at school stages) before it is essential to invoke the other levels. However, mathematics faces similar problems to chemistry in that many levels are needed quite early in learning.

The triangle model has proved to be powerfully useful. Nonetheless, it is sad that this kind of insight does not appear in teacher education courses. This raises questions about whether the education world really takes education research seriously (Read, 2015). The evidence shows that most entering school teaching copy the way they were taught at school (El-Sawaf, 2007), evidence from research playing little part.

In the 1990s, Johnstone was required to write the preface of a commissioned monograph entitled, *Creative Problem solving in Chemistry* (Johnstone, 1993). Facing this task, he realised that he did not really know what he meant by a problem or what problem-solving really was. He came up with a very simple, yet powerful, analysis.

In every problem in every area of life, there are three factors involved: what we know, the method to be used, the goal for the problem. It is very insightful to watch motor mechanics faced with a car that will not start. They know things about how an engine works (or can be made to work), they have various tests they can apply and various tools they can use. Their goal is simple: start the engine.

What Johnstone realised was that, in any problem in chemistry, we either know everything we need to know (or do not), we either have (or do not have) a known method to solve the problem, we know clearly what the goal is or the goal is unclear. This leads to eight types of problems (Table 1):

Table 1: Eight problem types (Johnstone, 1993).

Type	Data	Methods	Goals
1	Given	Familiar	Given
2	Given	Unfamiliar	Given
3	Incomplete	Familiar	Given
4	Incomplete	Unfamiliar	Given
5	Given	Familiar	Open
6	Given	Unfamiliar	Open
7	Incomplete	Familiar	Open
8	Incomplete	Unfamiliar	Open

Most problems we set in chemistry are "*type 1 problems*". We provide the data, the students have been taught the method, the required goal is specified (Bennett, 2008). Essentially, these are exercises or algorithmic problems (Kempa & Nicholls, 1983). However, in real life, most problems are not type 1. Often, we do NOT possess all the information we need. Often, we do NOT have some set method to apply. In addition, in many areas of life (including many areas of chemistry) we are not quite sure of our destination!

Johnstone never suggested that there is any hierarchy of difficulty. Thus, he stated quite clearly that these are simply eight *different* types of problems: difficulty and problem type are unrelated. A later study confirmed that (Reid & Yang, 2002). However, he did give us a simple way to classify problems. We can then analyse what we are doing with our students. Of course, there is a place for the algorithmic type of problem but there is also a place for a much wider range of problems, this reflecting more accurately the real nature of chemistry enquiry (as well as wider life). More recent work has developed and applied the ideas further (St Clair-Thompson, Overton, & Bugler, 2012; Tsaparlis & Angelopoulos, 2000; Tsaparlis, 2005).

Johnstone also made very large contributions in the areas of assessment (Johnstone, McCarron, & Morrison, 1970) and attitude development (Hadden & Johnstone 1982; 1983a; 1983b). In his early work, he revealed major flaws in the use of multiple choice question formats (Friel & Johnstone 1978a; 1978b; 1979a; 1979b; 1988). He then introduced a new way to assess the development of conceptual understandings using an objective format (Bahar, Johnstone, & Hansell, 2000; Johnstone & Ambusaidi, 2000). In the area of attitudes, three seminal papers laid the foundation (Hadden & Johnstone 1982; 1983a; 1983b) while the principles underpinning attitude development were outlined (Johnstone & Reid, 1981). Later work built on this and much is now summarised (Mbajiorgiu, Reid, & Ezeano, 2017; Reid, 2015).

Bringing it together

In a career that spanned over 50 years, Johnstone made a remarkable contribution to the world of chemistry education research. He never lost his love of chemistry. He never lost sight of young learners as they struggle to make sense of the complex ideas that underpin any understanding of the molecular world and its interactions. He was always willing to assist learners as they tried to make sense of their world in understanding chemistry, whether he was working with a 12 year old school student or a PhD student grappling with complex data in an attempt to make sense of learning.

His methods and approaches tended to be quantitative. He replicated experiments related to learning and understanding. He never relied on questionnaires, focus groups or interviews in that all these can do is collate the opinions of others. He never asked intending student to generate some "*project proposal*", or write pointless research questions. He knew what was known, he knew the next stages needing enquiry and he directed students into these areas of research. Indeed, his research direction followed the established approaches that have proved so successful in the sciences and many other disciplines. Of course, his target of enquiry was different. He wanted to explore and understand the complex nature of learning in the context of chemistry and related disciplines.

He was never side-side-tracked into abstract educational ideas or speculative "*theories*". His lectures and publications are characterised by clarity, the true sign of genuine understanding as well as brevity and rigour (for example, see Johnstone et al., 1998, for an example of rigour and clarity). He never confused erudition with abstraction: he never "*dressed up*" ideas with complex language. Indeed, he took complex ideas and *reduced* these to simple models that are accessible and helpful.

His methods were rigorous and powerful. Creativity was allowed to run free. Many of his research students started at one point and then went off in all kinds of directions during their research as findings pointed to new issues that were worth following up. Tragically, that is rarely seen in educational research where the demand of project proposals and research questions almost pre-determine the "*answers*". Generations of research students have expressed their gratitude for what he did for them and many have moved on to make their own contributions in their own countries. He received numerous awards:

- The Nyholm Medal of the Royal Society of Chemistry
- The Mellor Medal of the Royal Australian Chemical Institute
- The Illuminati Gold Medal of the Italian Chemical Society
- The Brasted Medal of the American Chemical Society
- American Chemical Society Award for Achievement in Research for the Teaching and Learning of Chemistry
- The Verhagen Titular Chair of the University of Limburg, Belgium

University chemistry departments in many nations have appreciated the impact, significance and relevance all his work. Sadly, that appreciation did not spread into wider education and it is regrettable that his insights have not found their way, in general, into schools of education. School teachers have often found the insights helpful but they lack the opportunity to change curricula or teaching methods easily, much being driven (and often hindered) by outside influences including high-stakes testing.

He has left a legacy of powerful insights, as well as a long list of publications, a few of which are referenced in this paper. He has left numerous areas where we, the next generation, must build on what he found. The goal for us has not changed. As teachers of chemistry, we want to equip the young people of the future to understand something of the remarkable contribution chemistry has made to our societies and cultures: to make chemistry exciting and accessible. For some, our goals will be to give these students a sufficient understanding so that they can carry forward the research enterprise to bring further understandings and, hopefully, benefits. His major contributions can be summarised (Figure 8).

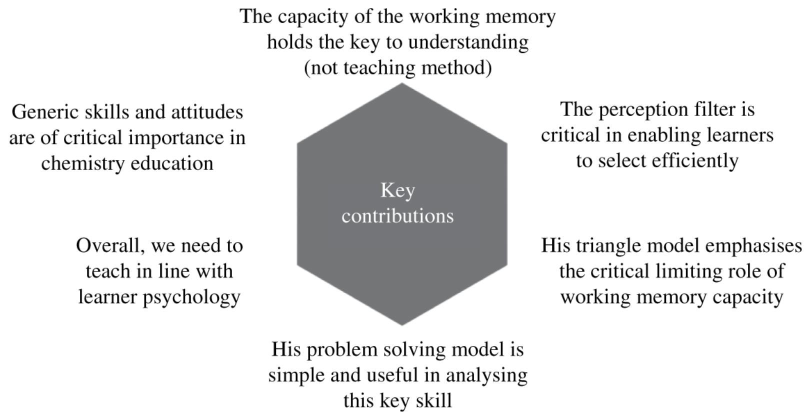

Figure 8: Key contributions.

He has generated an agenda for teachers of chemistry (Table 2) (see Johnstone, 2000a):

Table 2: An agenda for action.

An agenda for action	
Reduce curriculum coverage:	Give time for understanding
Change our goals:	Emphasise thinking and understanding
Remember working memory:	This controls all understanding
Re-think laboratory work:	Change our goals, use pre-labs
Increase group activities:	To allow skills development
Focus on education through chemistry:	The future citizens

The secrets of his success lie in four characteristics:

- His goal was always to make chemistry more accessible and more exciting for learners.
- He employed rigorous measurement methods, subject based, replicable.
- He never lost his love for teaching chemistry.
- His creative talents were allowed to run free.

He leaves behind, among many other things, two central principles

> If we understand the natural way all humans learn, then we can adjust our teaching to lead to better outcomes
>
> If we adjust our teaching to lead to better outcomes, then our students will be enthusiastic and motivated

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Notes

1 At that time, Scotland had an examination structure based on
Ordinary Grade (2 year courses: typically 7 subjects: age 14–16)
Higher Grade (1 year course: typically 5 subjects: age 16–17) – basis of university entrance
Certificate of Sixth Year Studies (1 year course: typically 3 subjects: age 17–18) – courses designed for educational benefit.

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